Development and Testing of a 20-kW X-Band Transmitter With High Phase Stability

R. Cormier and T. Tesarek
Radio Frequency and Microwave Subsystems Section

A new 20-kW X-band transmitter has been built and installed on the antenna at DSS 13. A description of the hardware and operation are presented. This transmitter is the prototype for the new X-band uplink to be added to the DSN to support Galileo and future missions.

I. Introduction

The design for an X-band uplink transmitter began in June 1979 to provide uplink capability in the frequency range of 7145 to 7235 MHz. By June 1982, a model of this transmitter was installed at DSS 13. Since then it has been operated intermittently for the purpose of evaluation before incorporating subsequent units into the Deep Space Network.

Some of the significant results obtained were the testing of the S-X feedcone assembly, distributed control, and phase stability. The S-X Feed test results have been reported (Ref. 1).

The klystron tube selected is a Varian Associates Model VA-876. Extensive testing and evaluation were made and the results reported earlier (Ref. 2).

The Exciter and Control systems have been reported on by R. Hartop, et al. (Ref. 3). The Control system has been changed since and the modifications will be covered in this report.

This report contains a description of the transmitter as configured at DSS 13. Operational results, modifications, and possible changes or alternatives for the transmitters to be placed into the Deep Space Network will be presented, as well as early results of its phase stability.

II. Hardware

The transmitter hardware at DSS 13 is distributed with parts or assemblies located on the ground, and other parts located in and around the antenna deckhouse and feedcone assembly. The motor-generator set and its controls, the beam power supply, and the controller are located at ground level, while the klystron assembly along with its input and output RF assemblies, the associated low voltage supplies, and some signal processing equipment are located in the feedcone. The heat exchanger is located just outside the deckhouse on the antenna. Fig. 1 is a block diagram of this transmitter. A brief description of the most important features of each of the major assemblies along with possible alternatives is presented. The operating parameters are summarized in Table 1.

A. Power Amplifier Assembly

The power amplifier (PA) enclosure is a compact unit measuring 61 cm wide, 53 cm deep, and 97 cm in height (Fig. 2) with all the joints and removable panels made to have metal contact for best RF shielding integrity. Three of the enclosure's sides and the top are removable for ease of maintenance and klystron removal. The fourth side serves as a mounting surface for the output waveguide structure and buffer amplifier assembly (Fig. 3). Klystron coolant connections are located on the top panel and consist of AN-type flare bulkhead fittings.

The enclosure is divided into three compartments. The upper compartment contains the Varian VA-876 klystron, the focus magnet, and the RF power monitoring circuits. One of the lower compartments contains the filament transformer, cathode cooling fan, and high voltage connection. The other lower compartment contains filament control circuits and interfacing terminal boards. The filament control circuit includes a "step start" sequence. During the first 5 minutes of filament "warm-up," a series resistor is inserted into the filament primary circuit to limit inrush current. When the initial 5 minute time delay is complete, the series resistor is switched out and a second 5 minute time delay begins to complete filament warm-up. Final filament voltage is set by an adjustable autotransformer in the primary circuit.

The output waveguide structure (Fig. 4) consists of a harmonic filter, arc detector, directional coupler, waveguide switch, and water load. The entire assembly is water cooled and was fabricated as one unit. This has the advantage that all waveguide flanges have been eliminated except for the input and output. It has the disadvantage that it must be completely replaced if a problem develops with any part of this assembly.

The buffer amplifier, mounted on the back panel of the PA cabinet, receives a low level drive signal (7145 to 7235 MHz) which is amplified by a two-watt solid-state intermediate amplifier. Drive on/off, drive level, and RF-path switching commands are received from the buffer control chassis located in the instrumentation rack. Drive level and switch position indications are also sent to the buffer control chassis. Another feature of this unit is a local oscillator and RF test port for independent transmitter testing, or for use when the receiver/exciter drive signal is not available.

B. Instrumentation Cabinet

The four-foot instrumentation rack, mounted next to the PA enclosure in the feedcone, contains a control/monitor interface chassis (Fig. 5), buffer control chassis (Fig. 6), and focus magnet and system DC power supplies (Fig. 7). The front panel has indicators and controls associated with the operation of the power amplifier only. In the original design an Intel ICS-80 microprocessor assembly did the signal conditioning and control functions for the power amplifier and heat exchanger. The distributed control approach was abandoned in October 1982 for the use of a central processor control located at ground level. A multiconductor cable was added for communication between the antenna and the ground equipment.

The control/interface chassis provides signal conditioning, interlock summing logic, and command control interface. Also included are optical isolator PC boards to isolate antenna mounted equipment from ground-based units when multiconductor interconnect cables are used. Signal conditioning is required for turbine flow meter and analog indications since the microprocessor accepts only 0 to 5 VDC full scale analog signals.

All protective interlocks associated with antenna-mounted equipment are logically summed at this point and a single "PA ready" indication is sent to the high voltage power supply via a "hard wire" interlock (I/L) cable. At the high voltage power supply, the PA ready is summed with ground-based interlocks and an absence of this indication will prevent the beam voltage from being activated.

The command control interface PC board serves the purpose of isolating commands from different points of origin, such as microprocessor, local control, or remote control. The buffer control chassis contains control/monitoring circuits and DC power supplies required for the operation of the buffer amplifier.

C. Heat Exchanger

Since the azimuth wrap-up at DSS 13 could not accommodate an extra set of coolant lines required for a ground-based unit, the heat exchanger (HE) was installed (Fig. 8) on one of the platforms above the azimuth bearing. Individual components of the heat exchanger were mounted on the platform in such a way as to provide easy access for service and maintenance. The radiator core and direct drive fan/motor are mounted vertically on the edge of the platform providing a side-discharge air flow away from the antenna structure. The radiator has been successfully tested with a 100-kW heat load. Coolant temperature during this July weather test was maintained within 15°C above ambient. Since coolant temperature fluctuations affect the phase stability of the klystron, the following features were incorporated into the heat exchanger:

(1) A 200-gallon surge tank reduces rapid temperature fluctuations.

(2) Two 18-kW tank heaters provide for cold weather operation.

(3) A three-way modulating valve bypasses the radiator to maintain a set temperature.

(4) A temperature controlled louver on output side of the radiator core is provided.

(5) The direct drive fan/motor is temperature controlled.

The cycle of items 2 through 5 provide coolant stability about a preset, fixed temperature setting.

D. High Voltage Power Supply

The high voltage power supply assembly (Fig. 9) consists of a metal enclosure with two compartments. One compartment contains the high voltage unit, the other contains the crowbar unit and beam voltage monitoring circuits. Attached to one end of the enclosure is a six-foot instrumentation rack which houses control panels, a high voltage control chassis, a computer, and motor-generator field power supplies. Separation of the control and monitoring circuits from the main high voltage section provides necessary shielding of EMI radiation generated by the high voltage section and the crowbar assembly. In addition, all wiring within the crowbar and high voltage sections is run through conduit to further minimize false triggering of control logic and interlock circuits. The high voltage section (Fig. 10) of the power supply contains a high voltage transformer, choke, rectifier stacks, and filtering networks. Input power of three phase 0 to 480 Vac, 400 Hz is applied to the high voltage transformer and stepped up, rectified, and filtered with an output of 20.0 kV at 3 amperes DC. A standard 20-kW S-band high voltage supply was used with only the step-up transformer being changed because an inductrol was not used.

The present S-band 20-kW transmitters in the DSN have fixed output voltage 400-Hz generators. The beam voltage is adjusted by the use of an inductrol, but it is not regulated. The inductrol is set by the operator and no adjustment of beam voltage is made automatically. The regulation is better than 1%. For the developmental X-band transmitter, a field variable generator is used which is part of a closed-loop regulator. The regulation is maintained to 0.1%. A similar means of adjusting the beam voltage is also used by Spacecraft Tracking Data Network's version of the S-band transmitters, except that the regulator controlling the field current of the generator is operated open loop.

An alternative is the use of thyristor phase control at the input to the high voltage transformer. The advantages are: (1) a closed-loop regulator can be implemented with better regulation than can be obtained with a field control generator, (2) the use of thyristors is more reliable and requires less maintenance than a generator, and (3) the fast turn-off capability of thyristors would make it possible to eliminate the crowbar. This alternative is being investigated for the X-band transmitters for implementation into the DSN.

The crowbar section (Fig. 11) contains a dual ignitron crowbar assembly, body current detector, and high voltage dividers for beam voltage monitoring. In the event of a klystron-beam intercept, the crowbar will remove beam voltage from the klystron within 10 microseconds.

The instrumentation rack (Fig. 12) contains all necessary manual transmitter controls and indications. The high voltage control chassis monitors beam voltage levels and provides drive to the motor-generator field power supplies.

E. Motor Generator Set

The motor-generator (Fig. 13) set is a 75-kW unit with a separate start/stop and protection circuit J-box. The generator field is controlled by the high voltage control chassis. This provides a closed-loop system and a regulated high voltage power supply.

III. Software Development

The control system planned for the X-band uplink transmitter was to consist of a microprocessor controller for each major subassembly, namely, one for the power amplifier, another for the heat exchanger and a third for the power supply. In addition, a central master controller was to interface the transmitter with either local operator (or maintenance terminal) or with an interface controller for automatic operation. This arrangement is described in Ref. 3.

However, the use of a controller at the heat exchanger would have been difficult because the heat exchanger is unsheltered and no controller capable of operating in the outside environment was readily available. The heat exchanger was located in close proximity to the power amplifier. A multi-conductor control cable from the heat exchanger to the power amplifier was therefore used to control the heat exchanger directly by the power amplifier microprocessor.

Development of a distributed microprocessor control system with four controllers, (1) the interface controller for station control, (2) the master controller to coordinate the total transmitter operation, (3) the power supply controller to provide high voltage supply signal and fault processing, and (4) the power amplifier to provide the klystron's signal and fault processing, proved to be unwieldy. Three factors led to the abandonment of this arrangement.

Firstly, this system is over-complicated. The program and signal information were duplicated in three microprocessors. In order for the power amplifier controller to perform its function it was necessary to obtain real time status information from the power supply controller.

Second, communication between the various processors caused unacceptable delays. This problem was further aggravated by failures in the optic cable utilized for communication between the power supply and the power amplifier controllers. After multiple breaks and splicing of the optic cable the losses required the addition of amplifiers.

The third factor was compatibility with the S-band transmitter, namely, the requirement to include both S- and X-band transmit capability. The S-band transmitter power supply, heat exchanger, and cables were to be utilized with two power amplifiers, one at X-band and one at S-band. In the S-band a central controller had been developed with all controls hand-wired between the various subassemblies.

Because of these factors and because of schedule and budget constraints a central processor control was therefore implemented. The central processor control had been operating the high-power S-band transmitter at DSS 13 and it was relatively easy to adapt to this transmitter.

An X-band transmitter simulator was designed and assembled. The simulator is a hardware type and provides the same functions as the X-band transmitter when connected to the controller. This allows the testing of software without any risks of damaging equipment or the expense of operating a full transmitter subsystem.

IV. Software Description

The Local Transmitter Controller (LTC) operates the Transmitter Subsystem (TXR) (see Fig. 14) in an unattended sequence of operations, beginning with system turnon through calibration and culminating in a tracking pass. The LTC monitors the operations of the TXR and submits progress, status, and operational data to display terminals at the Local Control Console (LCC) and the Remote Control Console (RCC). The LTC does not override the internal protection circuitry of the TXR, nor does it prohibit manual intervention by maintenance personnel. If difficulties arise during operation the LTC will alert the operator; then, if the problem is corrected within the operational parameters of the TXR, the LTC will continue to provide automatic control. Otherwise, the operator elects to use the LTC to return the TXR to the off state or to control the TXR manually via the LCC. A brief description of the monitor and control functions of the LTC follows.

Transmitter performance and parameters reported to the operator includes, but is not limited to:

(1) Power output: XX.X kW.

(2) Drive status: on/off.

(3) RF load: antenna/waterload.

(4) Interlocks: reports I/L name if active.

(5) Configuration: transmitter or simulator.

(6) Beam voltage and current: XX.X kV and XX.X A.

(7) Drive power: XX.X MW.

(8) Filament voltage and current: XX.X V and XX.X A.

(9) Magnet current: XX.X A.

(10) Reflected power: XX.X W.

(11) Vacuum current: XX.X μA.

(12) Body current: XX.X MA.

These parameters are sampled at approximately 1 second intervals and displayed on both the local and remote terminals.

Either terminal accepts the following high level command and performs the associated functions without operator intervention.

(1) WAR.

(2) CAL.

(3) PWR XX.X.

(4) STB.

(5) OPR.

(6) OFF.

The WAR command causes the LTC to: turn on the control power supply, MG set, magnet, and filament supplies; wait for the filament time delay to be completed; and, inform the operator when the TXR is ready for calibration.

The CAL command causes the LTC to perform a crowbar test; perveance test; and to saturate the transmitter at the default or requested power level. Following completion of the calibration phase, the LTC removes beam voltage, enters the standby state, and announces that it is ready to operate.

The OPR command causes the LTC to raise the beam voltage to the value settled upon during the calibration phase. Then, following a short delay to allow beam voltage to raise, the LTC informs the operator the status of the following operating parameters:

(1) Output power level.

(2) Saturated or unsaturated mode.

(3) Antenna or waterload.

The STB command causes the LTC to go from the operate to the standby state. The beam voltage is lowered and the LTC announces that the TXR is in the standby state.

The OFF command causes the LTC to begin a shutdown sequence that returns the TXR to the pre-warm-up state. The beam voltage, then drive power, filament voltage and magnet voltage are removed in that order. Finally, the MG set and control power are turned off and the displays are re-drawn.

The PWR XX.X command causes the LTC to use the value XX.X in kW, as the target value for output power during the calibration phase; or, following a request to "SEND CAL," to recalibrate the output power at the new value provided by XX.X while in the operate state.

The LTC interfaces with the TXR via a junction panel as shown in Fig. 15. The firmware needed to perform the functions discussed above is resident on the BLC 8432 prom board. It consists of about 20K bytes of code that was developed using an Intel MDS 800 system, with ISIS operating software, and Intel's PLM80 compiler. Digital interfacing with the many interlock, etc., indicators was provided via the I/O Expansion Board BLC 519. Analog interfaces were provided via a 12-bit analog to a digital, differential input, converter. Including spares, a total of 24-analog and 72-digital input signals are accommodated. Local storage for the status of these signals, along with other variables, is provided by a core memory MCM 8080 board. Twenty-four output signals required to activate relays and motors involved in the control of the TXR are provided on the system CPU board. Signal conditioning and isolation for the interface signals is provided by the computer interface chassis. An RC pi-filter is used in each pair of analog input lines and opto-isolation is provided for all digital input and output lines.

V. Tests

The X-band transmitter has provided the means to perform system tests with associated equipment and, as a consequence, make modifications to various uplink subsystems. The transmitter contributed to the development of S-X band feed assembly, of the diplexer, of the phase correction loop, and of the software. The S-X feed assembly and diplexer development was reported in Ref. 1. Since that report the two-cavity band stop filter has been reworked and the design goal for the receive band isolation/rejection ratio of 73 dB has been met. Simultaneous S- and X-band has been operationally tested. A future report will discuss system noise temperature effects and intermodulation product investigations.

A problem encountered with the phase correction loop forced a decrease in loop gain from 100 to 40. (This has since been analyzed and a new design is now possible with a gain of 100.) The phase loop, consisting of a single pole transfer function, tracks the carrier and has two bandwidths. The 120-Hz wide bandwidth is utilized to correct for 60-Hz modulation. The narrow bandwidth of 3 Hz is utilized to correct for drifts. This phase correction loop does not affect the phase modulation.

The Allan Variance stability of the uplink carrier was measured at the output of the transmitter. Measurement values varied from 0.5 to 1.4 parts in 10^{15}. This represents 6 measurements performed in April and May of this year, and at various times of the day or night with commercial and with diesel prime power. The worst data was obtained between 5 a.m. and 7 a.m. with commercial power. It might be advisable to use diesel power during this time period for the Galileo gravity wave experiments.

There is a phase correction loop from the output of the transmitter to the input of the exciter. Both the transmitter and the exciter have been tested individually with this loop opened and closed. The exciter open-loop measurement values varied from 0.6 to 1.35×10^{-15}, while the closed-loop values were consistent at about 0.7×10^{-15}. The test instrumentation did not allow the transmitter to be measured separately. The uplink chain was measured with the transmitter and the phase loop opened. With the transmitter operating in a saturated power mode, values of 1.13 to 2.05×10^{-15} were obtained. In an unsaturated mode values of 1.06 to 1.85×10^{-15} were obtained. A small improvement may be obtained by operating the transmitter unsaturated. The effect of the transmitter on the uplink carrier can be seen by comparing the exciter data and the exciter and transmitter combination, both with the phase loop open and closed. The variability of the data is due to prime power stability and ambient temperature variations. Improvement can be obtained by tighter supply regulation and stabilization of coolant temperature and flow rate. Phase stability tests are continuing and will be reported for all the applicable subsystems in the future.

VI. Conclusion

The successful operation of the X-band transmitter at DSS 13 has provided a prototype for the development of the hardware necessary for X-band uplink. This technology is now in the process of being transferred to the implementation of X-band transmitters in the DSN which will provide support to Galileo and future spacecraft. In addition, the improved stability will provide new capability in the performance of precision measurements such as the possible detection of gravitational waves.

References

1. Withington, J.R., "Second-Generation X/S Feedcone: Capabilities, Layout and Components," *TDA Progress Report 42-63*, Jet Propulsion Laboratory, Pasadena, Calif., June 15, 1981.

2. Kolbly, R.B., "Evaluation of the VA-876P Klystron for the 20 kW X-Band Uplink Transmitter," *DSN Progress Report 42-54*, Jet Propulsion Laboratory, Pasadena, Calif., December 15, 1979.

3. Hartop, R., Johns, C., and Kolbly, R., "X-Band Uplink Ground Systems Development," *DSN Progress Report 42-56*, Jet Propulsion Laboratory, Pasadena, Calif., April 15, 1980.

Table 1. Transmitter characteristics

Parameter	Value
Power output, kW CW	20
Frequency band, MHz	7145 to 7190
Instantaneous band, MHz	45
Track duration, h	12
Transmitter uncompensated, ($\Delta F/F$)	3×10^{-15} over 1000 s

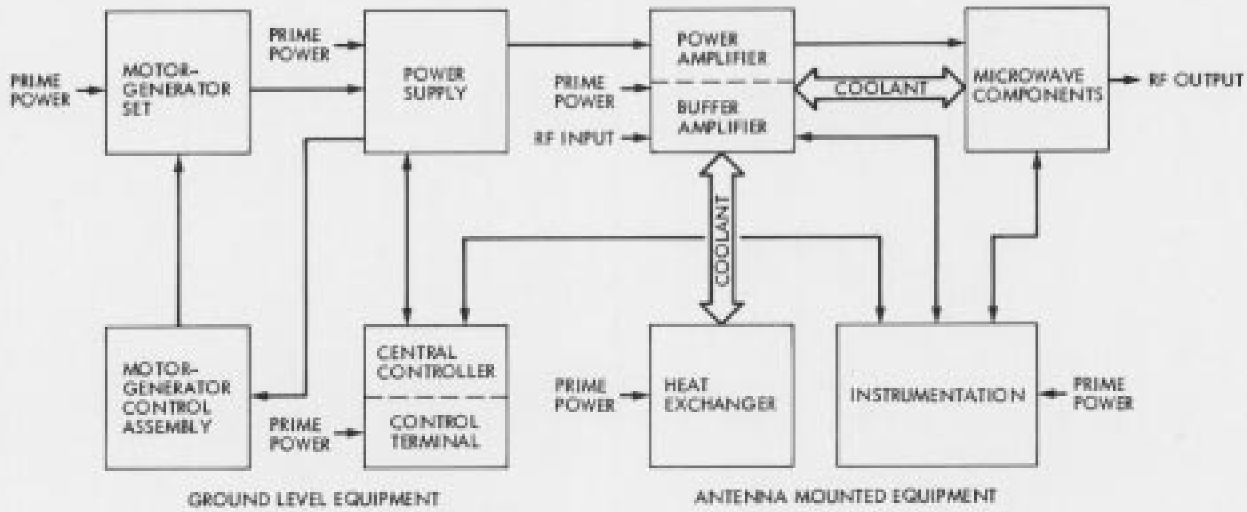

Fig. 1. Equipment block diagram 20-kW X-band transmitter prototype at DSS 13

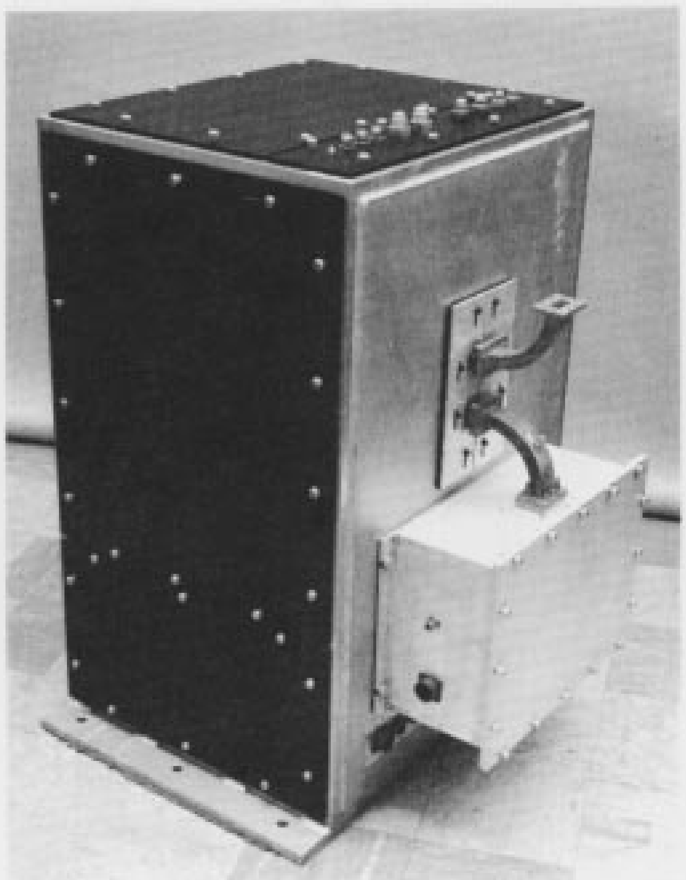

Fig. 2. Power amplifier

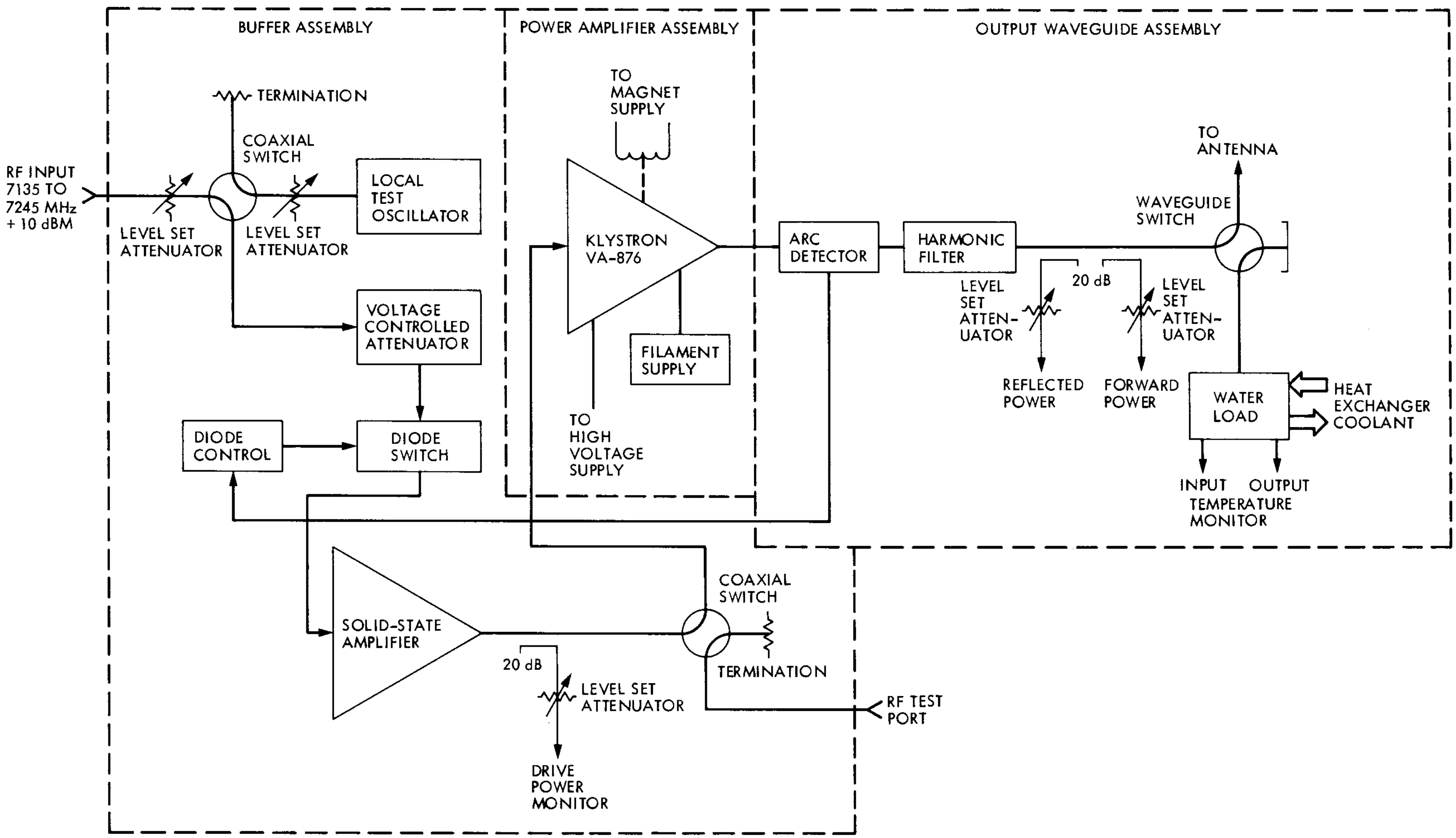

Fig. 3. Block diagram of power amplifier

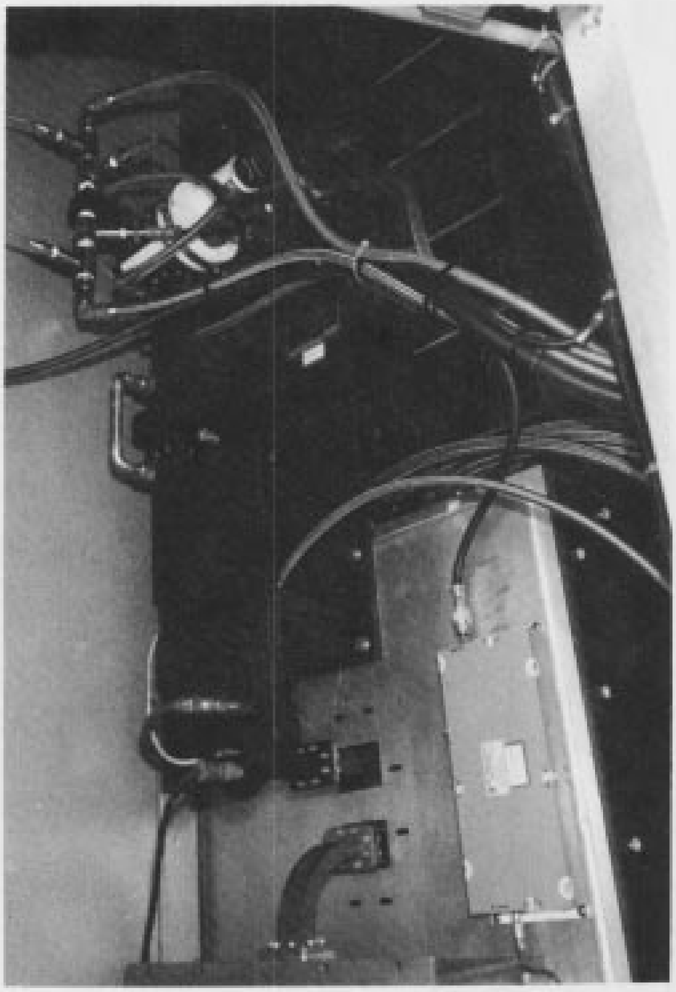

Fig. 4. Output waveguide

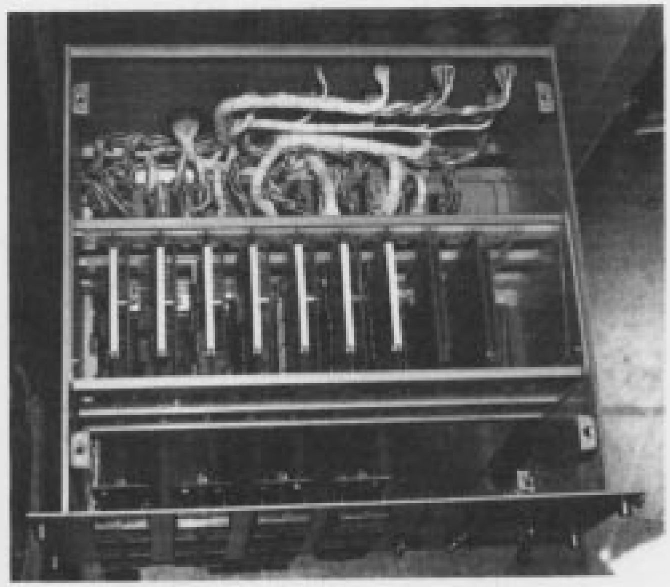

Fig. 5. Control/monitor interface chassis

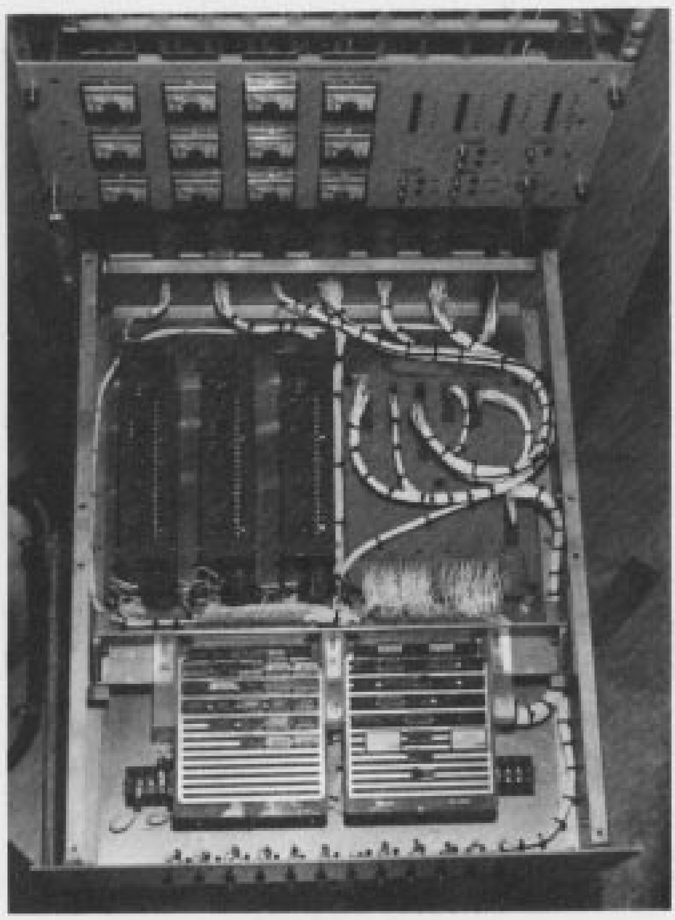

Fig. 6. Buffer control chassis

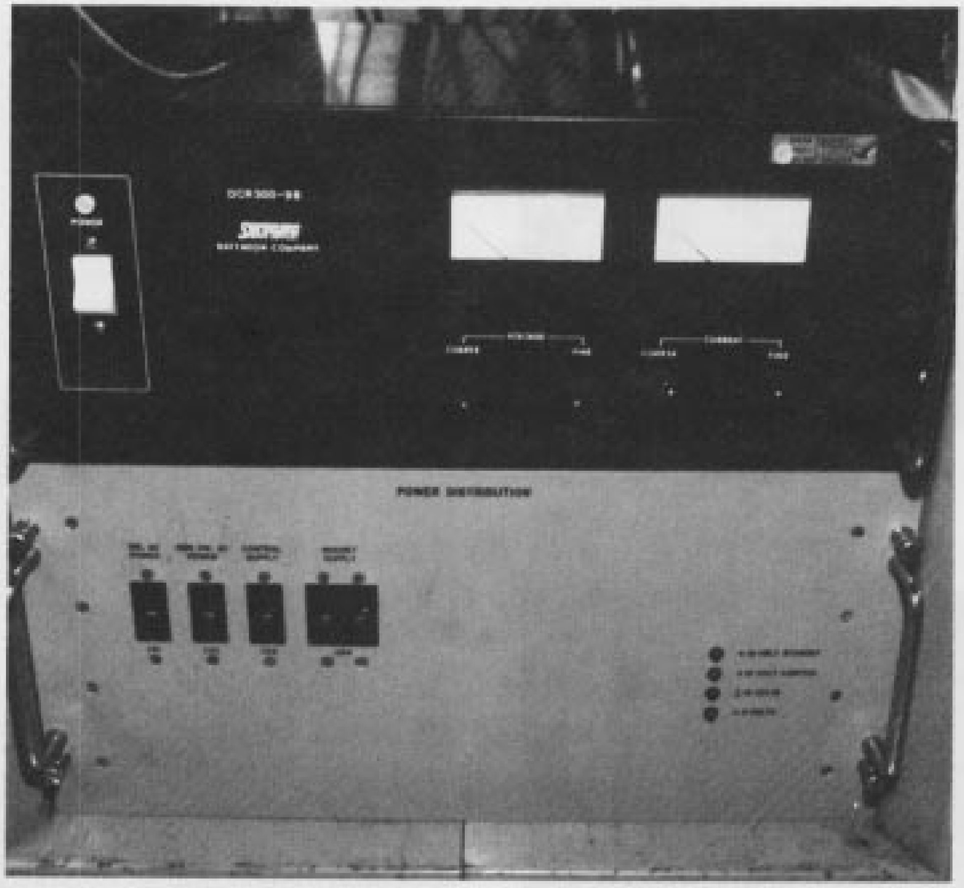

Fig. 7. Magnet and system DC power supplies

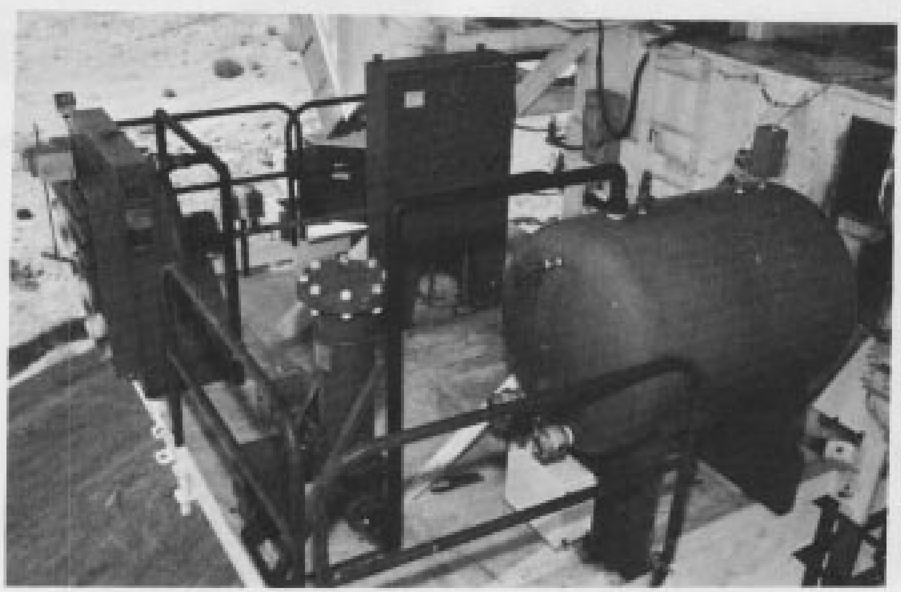

Fig. 8. Heat exchanger

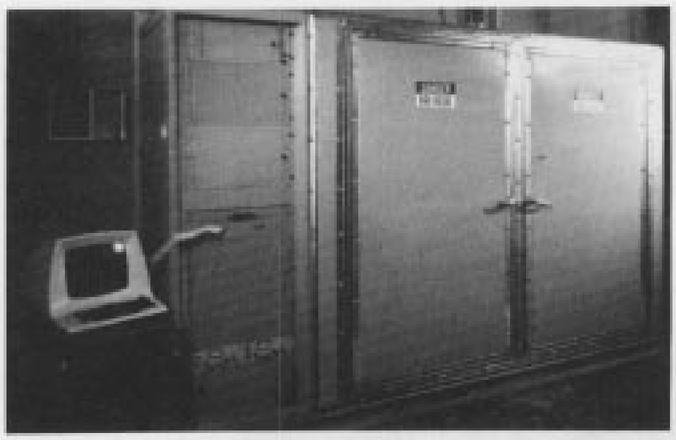

Fig. 9. High voltage assembly

Fig. 11. Crowbar assembly

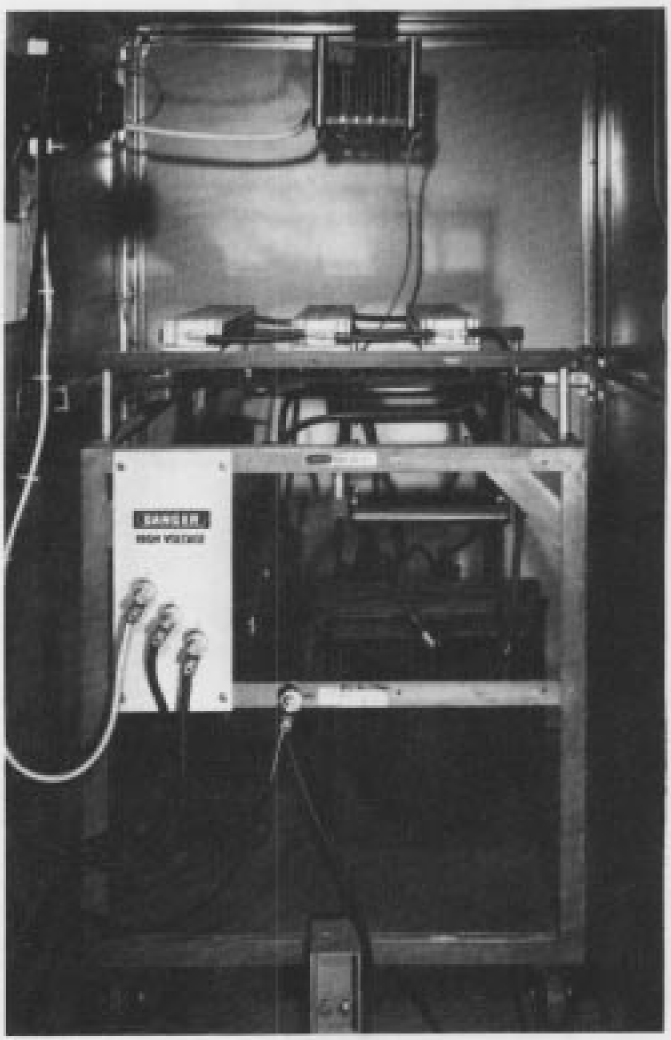

Fig. 10. High voltage section

Fig. 12. Instrumentation panels

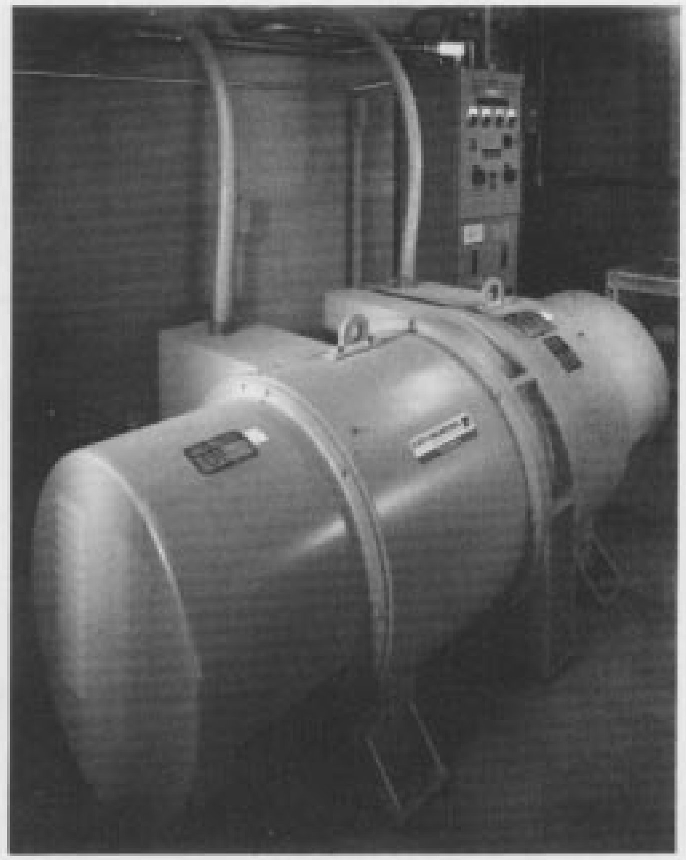

Fig. 13. Motor generator

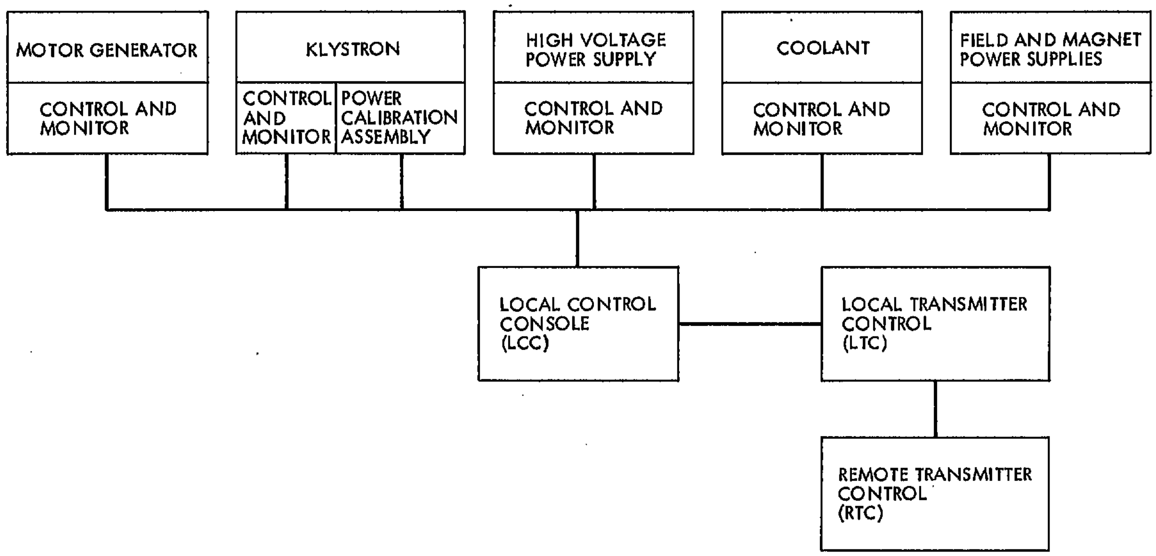

Fig. 14. Transmitter subsystem configuration X-band transmitter automation subsystem

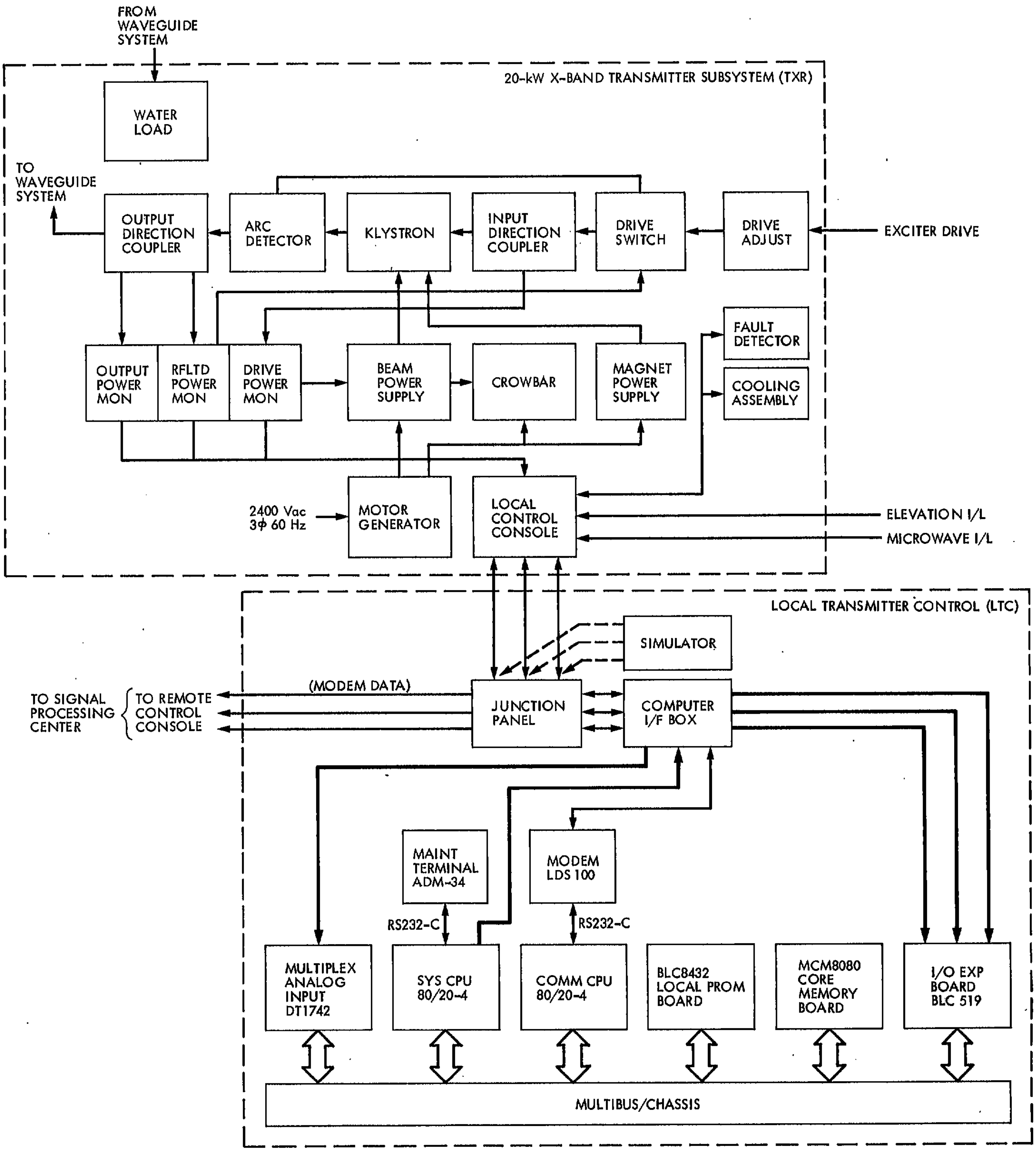

Fig. 15. 20-kW X-band transmitter